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摘　要：为了满足强激光系统中大尺寸镀金光栅对槽深均匀性的要求，采用梯形光栅-涂胶-离子束溅射镀膜和全息光刻-离子束溅射镀膜两种方法，分别制作了线密度为1 740线/mm，槽深为210 nm的宽带镀金正弦光栅．测得其TM波、−1级自准值平均衍射效率在750～850 nm范围内大于87%，最高可达90%．这两种方法易控制光栅槽深，去掉光刻胶后基底可继续使用，且制作的光栅的衍射效率和带宽能满足国内一般宽带镀金脉冲压缩光栅的使用要求．

关键词：全息光栅；全息干涉；光栅器件的研制；衍射效率；脉冲压缩
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Fabrication of Broadband Sinusoidal Gold-coated Gratings

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Abstract: In order to satisfy the requirements of large aperture broadband gold-coated gratings groove depth uniformity in the high-power laser system, Broadband sinusoidal gold-coated gratings with line densities of 1 740 lines /mm and groove depth of 210 nm have been successfully fabricated via the methods of trapezoidal grating-coating-deposition and holographic lithography-deposition. The average diffraction efficiency at the −1 order (Littrow mount) is above 87% and the peak value is 90% for TM polarized light spanning wavelengths from 750 to 850 nm. The experimental results show that Gratings groove depth can be easily controlled. After removing the coated photoresist, the substrate could be reused. Diffraction efficiency and bandwidth meet the requirements of the domestic general broadband pulse compression gold-coated gratings.

Key words: Holographic grating; Holographic interference; Grating components fabrication; Diffraction efficiency; Pulse compression
OCIS Codes: 050.1940; 050.1950; 050.1960; 050.2770

0 Introduction

With the development of laser technology, the fabrication of diffractive optical elements has greatly developed. Diffractive optical element is widely used in laser beam smoothing, large pulse compression system and laser beam sampling [1-3].

One of the core elements of high-power laser systems is Pulse Compression Grating (PCG). Now the PCG is mainly fabricated by the process combing

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holographic lithography and ion beam etching. The PCGs for high-power laser systems include Multilayer Dielectric Grating (MDG), Metal Multi-Layer Dielectric Grating (MMDG)[4-5] and gold-coated grating. Much of the works on PCGs have focused on MDG[6-8]. Gold-coated grating diffraction efficiency generally can reach 92%, the highest for the 95%[9]; The damage threshold of FS laser pulse is 0.67 J/cm^2[8,10], therefore the low damage threshold is its fatal weakness[11]. In order to meet the requirement of petawatt-scale laser pulse compression system, the size of gold-coated grating should be as large as meter-scale[12]. The challenges of fabricating large size broadband gold-coated grating are achieving high diffraction efficiency and uniform groove depth, which are determined by lots factors, such as: Coating the photoresist film; fringe stability long time holographic exposure and intensity distribution; control the grating groove depth in the developing process; the uniformity of gold deposition process etc. The Lawrence Livermore National Laboratory had fabricated two pieces compression gratings of 94 cm in diameter the early 90's with diffraction efficiency of 92.8% and 93.8% at 54° incident angle and wavelength of 1 064 nm[13]. They represent the best level of meter-scale gold-coated grating. Now only French Jobin-Yvon company and Plymouth Grating Laboratory of USA to do the gold-coated grating for the petawatt-scale laser pulse compression systems.

The study on fabricating BSGG is very limited so far in our country, more importantly, this kind of gratings can get high diffraction efficiency within a broadband range (usually 200 nm or more) [14]. Based on above advantages the BSGGs have gained lots of attention in the fields of the short-pulse (shorter than 100fs), high-power laser pulse compression systems. So this paper focuses on the fabrication techneque of high diffraction efficiency and uniform BSGG. BSGGs with line densities of 1740 lines /mm and groove depth of 210 nm have been successfully fabricated via the methods of Trapezoidal Grating-Coating-Deposition (TGCD) and Holographic Lithography-Deposition (HLD).

1 Fabrication of broadband sinusoidal gold-coated gratings

In order to improve the quality of BSGG, the grating grooves need to be uniform. It requires homogeneous light exposure and film deposition, precisely controlled development.

The grating belongs to sinusoidal amplitude gratings, so it only has the zero order and ±1 orders. The wavelength of incident light is larger than the grating period, and only vector method can be used to analyze the diffraction characteristics of grating. Fig. 1 is the theoretical calculation results of the BSGGs −1 order diffraction efficiency, groove depth and the wavelength of incident light, grating line density is 1 740 lines/mm. From Fig. 1, the area with diffraction efficiency above 92% is: groove depth 200～220 nm; wavelength of incident light 700～900 nm.

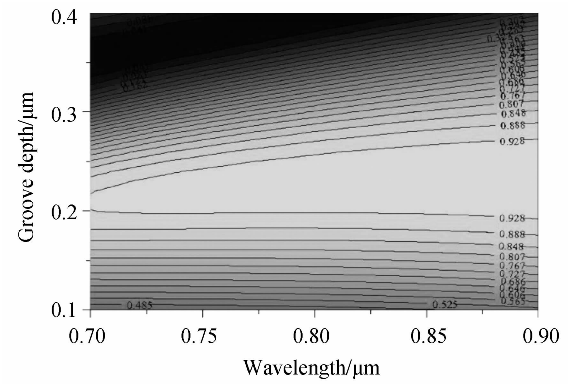

Fig. 1 Theoretical calculation results of the BSGGs −1 order diffraction efficiency, groove depth and the wavelength of incident light

1.1 TGCD method

The process is shown in Fig. 2. Firstly, a trapezoidal quartz grating is obtained using holographic lithography. Secondly, the grating is spin-coated with photoresist, then a sinusoidal photoresist grating is got. Before photoresist coating, quartz substrate were ashed to improve the photoresist adhesion. After coating, grating masks were baked at 90℃ for 45 min to harden the photoresist. photoresist grating groove depth was controlled to be 240 nm by adjusting the rotating speed and photoresist concentration. The basic law is that the more dilute photoresist and the greater speed lead to deeper groove depth of the photoresist grating which is detailed in section 2.

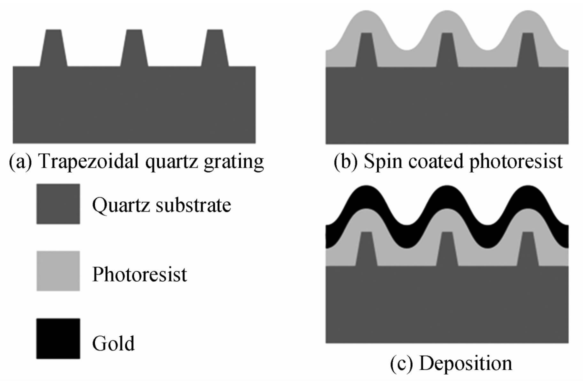

Fig. 2 TGCD fabrication process

Fabrication process: a) to obtain the quartz grating needed, grating groove depth is about 550 nm; b) coated with S1805 (3 photoresist: 1dilution), spreading speed is 1000 rpm, the sine shaped photoresist grating groove depth is 240 nm; c) deposition, gold thickness is 200 nm, BSGGs groove depth is 210 nm.

1.2 HLD method

The process is shown in Fig. 3. The photoresist film thickness was measured by a step profiler. By adjusting the spin time and rotating speed of the spinner, the photoresist thickness was controlled to be approximately 240 nm. After development, grating masks were baked at 90°C for 45 min to harden the photoresist. In this process, chose of photoresist, precisely control of the exposure and development durations are particularly important. Because, the photoresist is not too easy make into a sinusoid shape after exposure. if exposure and development duration is too long, groove shape will be changed; if exposure and development duration is too short, the groove depth will be smaller and leaving photoresist undeveloped , as shown in Fig. 4.

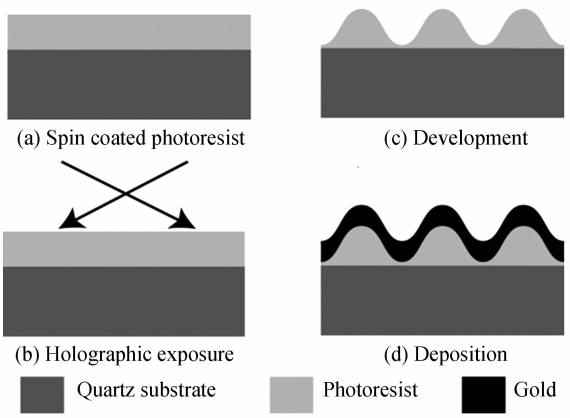

Fig. 3 Schematic of the HLD fabrication process

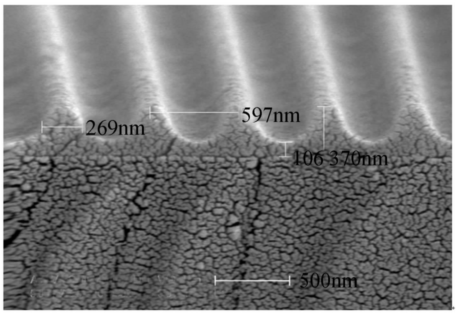

Fig. 4 The photoresist grating image when the exposure and development duration is short

Fabrication process: a) the preparation of a 240 nm thick AZ3100 photoresist layer on a quartz substrate after cleaning up; b) holographic exposure; c) development, the developing durations is controlled to get ideal sinusoidal photoresist grating and ensure that after development the grating groove depth is uniformly. d) deposition, gold thickness is 200 nm, BSGGs groove depth is 210 nm.

2 Results and discussion

In the TGCD method, for the same etching grating, only change the rotating speed, different rotating speed corresponding to different photoresist grating groove depth. As shown in Table 1. For K1, when the rotate speed is 2 000 rpm, the depth of the groove is 210 nm; when the rotate speed is 2 500 rpm, the depth of the groove is 246 nm. At rotating speed is same, photoresist concentration of different photoresist grating groove depth is different. For K1, when photoresist concentration is photoresist: dilution=3 : 1, the depth of the groove is 210 nm; when photoresist concentration is 1 : 1, the depth of the groove is 301 nm.

Table 1 Photoresist grating groove depth in different rotating speeds and concentration of photoresist (using S1805 photoresist)

No.	Groove depth after etching	Rotating speed/ rpm	Groove depth after coating/nm ph:d=3:1	Groove depth after coating/nm ph:d=1:1
K1	547	2 000	210	301
	547	2 500	246	352
K2	560	1 000	218	272
	560	1 500	255	303
K3	492	1 500	199	230
	492	2 000	211	246

For different gratings, in order to obtain the same groove depth, different rotating speeds are needed, with the same photoresist, as shown in Fig. 5.

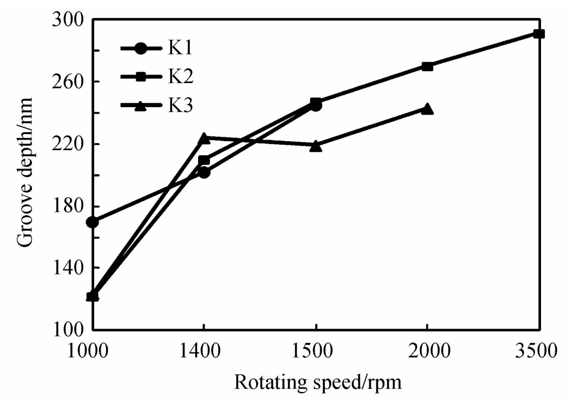

Fig. 5 Relationship between rotating speed and groove depth

Using the technique detailed above, desired photoresist grating structures were successfully obtained on three substrates (K1, K2, K3) with different groove depths and duty cycles, as shown in Fig. 6. The final BSGG can be got after gold deposition on the surface of sinusoidal photoresist grating. Moreover, the substrate is recyclable. After removing the coated photoresist, the substrate could be reused.

In the HLD method, the groove depth and duty cycle of the photoresist mask were controlled by adjusting photoresist thickness and durations of exposure and development , respectively , as shown in

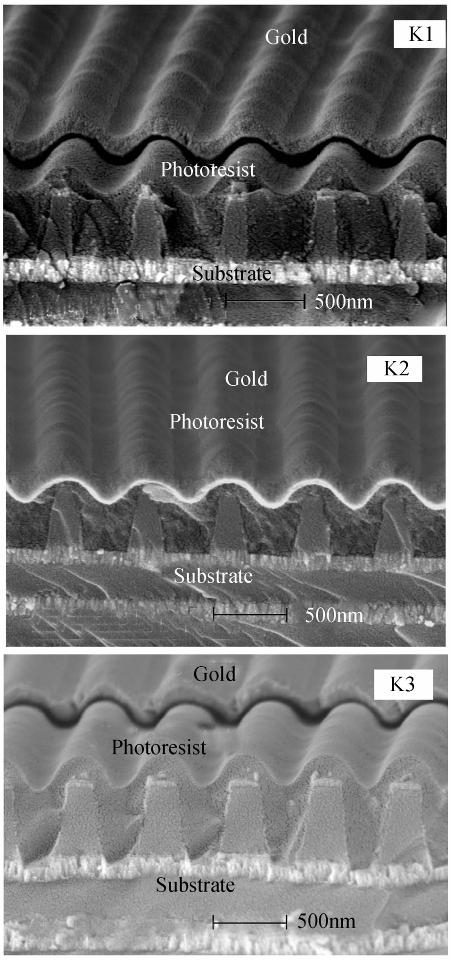

Fig. 6　BSGG with line densities of 1740 lines /mm, fabricated by the methods of TGCD

Fig. 7 where the duty cycle are 0.54, 0.58, 0.62, 0.47 respectively.

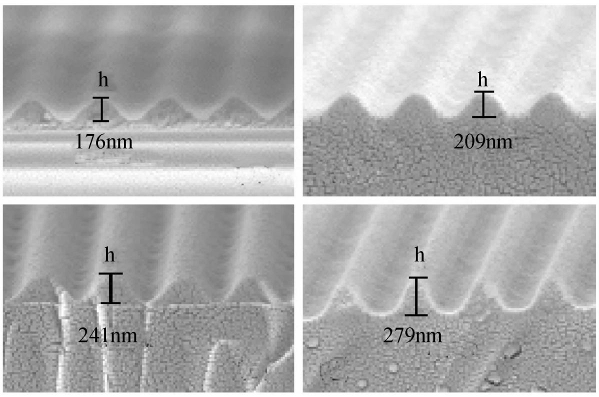

Fig. 7　Sinusoidal photoresist grating formation in HLD process

The final BSGG can be got after gold deposition on the surface of sinusoidal photoresist grating, as shown in Fig. 8.

Table 2 showed the BSGGs groove depth and diffraction efficiency, with different fabrication processes. The incident light is TM polarized light with a wavelength of 808 nm in the experiment. Measurement of diffraction efficiency is detailed in Ref. 15.

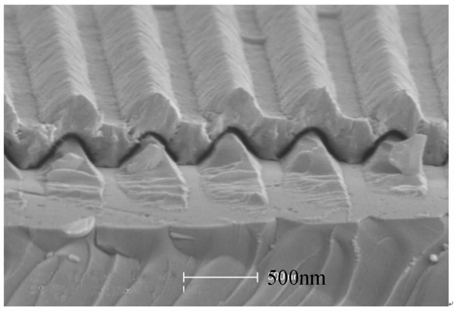

Fig. 8　BSGG with line densities of 1740 lines /mm and groove depth of 210 nm, fabricated by the methods of HLD

Table 2　The BSGGs −1 order diffraction efficiency fabricated by different process

No.	Groove depth after etching/nm	Groove depth after deposition/nm	Diffraction efficiency/TM
K1	547	225	80.13%
K2	560	210	88.02%
K3	492	196	84.74%
P_1		210	86%
P_2		182	81%
P_3		236	81%

The relationship between BSGGs −1 order diffraction efficiency and wavelength of the incident light are shown in Fig. 9. The groove depth is (1) 210 nm and (2) 270 nm, line density is 1 740 lines/mm. The results show that the experimental data are in agreement with the theoretical values, wavelength increases with increasing diffraction efficiency. In long wavelengths, the grating is closer to the Littrow mount and the gold reflectivity is higher, which are distributing to higher diffraction efficiency. The average diffraction efficiency at the −1 order (Littrow mount) is above 87% and the peak value is 90% for TM polarized light centered at 800 nm as the wavelength increases from 750 to 850 nm. Its diffraction efficiency has been measured in state key laboratory of precision measurement technology and instruments Tsinghua University.

As shown in Table 2 and Fig. 9, experimental

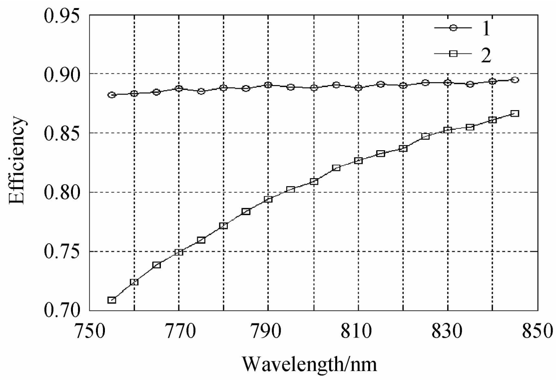

Fig. 9　Relationship between BSGGs −1 order diffraction efficiency and wavelength of incident light

diffraction efficiency is a little lower than theoretical value presented in Fig. 1. This is mainly caused by the fact that grating surface is not strictly a sinusoidal shape. In addition, the uneven deposition of gold film may also be responsible for the decrease of diffraction efficiency.

3 Conclusion

BSGG with line densities of 1 740 lines /mm and groove depth of 210 nm have been successfully fabricated via the methods of TGCD and HLD. Grating groove depth can be easily controlled in both methods. Uniform sinusoidal photoresist grating mask are obtained. Measurement results show that diffraction efficiency of the BSGGs are accordant with those from theoretical analysis. The substrate is reusable as long as the coated photoresist are removed.

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